Photoluminescence Studies of Two-Dimensional Electron Gas in Modulation Doped $Al_xGa_{1-x}N$/GaN Structures Grown on SI 4H-SiC by MOCVD

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1. Introduction

Electron devices with ever-increasing operating speed are used for applications such microwave switches or amplifiers. As the physical dimensions of these devices (e.g., field effect transistors) become smaller, thinner channel layers and higher electron concentrations are required to provide high performance operation. This is because current for faster discharge of capacitance in these microwave device structures is proportional to the carrier velocity as well as the carrier density. This requirement of large concentration of electrons can be met by novel hetero-junctions. In the case of aluminum gallium arsenide (AlGaAs) and gallium arsenide (GaAs), the junctions can be aligned so that the energy of the electrons and thus, the donors, is introduced only to the larger band gap AlGaAs material [1,2]. The electrons in the AlGaAs layer diffuse into the lower energy GaAs layer where they are confined because of the energy barrier. This modulation doping, i.e., doping of the barrier layer at hetero-interface, thus causes a redistribution of electrical charge across the interface. In the case of n-doped barrier layer, the region in the barrier closer to the interface will be depleted and the corresponding electrons will accumulate in a potential well in the active layer closer to the interface as a 2DEG [3]. Having the electrons thus confined at the hetero-interface in the 2DEG very close to the gate and an optimum interface leads to very high mobilities and large electron velocities at very small values of drain voltage. The 2DEG can be investigated by photo excitation, and the resulting radiative recombination between the 2DEG and photo-excited holes in heterostructures observed.

The recombination of 2DEG and its related PL has been studied recently by many workers [4,5]. Recently, recombination studies of 2DEG have also been studied extensively in $Al_xGa_{1-x}As/GaAs$ heterostructures [6,7].

AlGaN structures have different properties when compared to AlGaAs. For example, the offset of the PL energy band in AlAs/GaAs is about 0.75 eV, while in AlN/GaN, it is 2.8 eV. This indicates that the discontinuity of the conduction band is also large in the case of $Al_xGa_{1-x}N/GaN$ hetero-interface when it is compared with the discontinuity of $Al_xGa_{1-x}As/GaAs$ if the Al mole fractions are the same in both compounds. In addition, the piezoelectric effect is very strong in an $Al_xGa_{1-x}N$ layer on GaN. In such cases, electric polarization should occur, resulting in large charge densities and associated electric fields.

Recently, research effort on the $Al_xGa_{1-x}N/GaN$ heterostructure has begun to emerge. Bergman et al. [8] observed a broad PL peak about 50 meV below the free exciton emission of GaN in the $Al_{0.3}Ga_{0.70}N$ /GaN heterostructure and attributed it to the recombination between 2DEG and photo-excited holes at the hetero-interface. However, an accurate determination of the peak energy cannot be determined, since its intensity was weak and the peak was broad. Shen et al. [6] performed PL on modulation-doped $Al_{0.22}Ga_{0.78}N$ heterostructures. They found that the PL peak related to recombination between 2DEG and photo-excited holes at hetero-interfaces about 45 meV lower than the peak of the free excitons' (FEs) emission of GaN. They observed the peak at a temperature as high as 80K. Zhang et al. [9] observed a similar phenomenon in $Al_{0.09}Ga_{0.91}N/GaN$ heterostructures. They found that the PL peak related to recombination between 2DEG and photo-excited holes at hetero-interfaces was very broad and was about 150 meV lower than the peak of the FEs' emission of GaN. Kwon et el. [10] studied the low temperature PL of the $Al_{0.37}Ga_{0.63}N/GaN$ single heterostructure. At high intensity photo-

excitation, they found that the peak was attributable to recombination about 58 meV lower than the peak of the FE emission of GaN.

In this study, we investigated the PL spectra of the modulation-doped $Al_xGa_{1-x}N/GaN$ heterostructures at low temperatures and for different optical pump intensities. The PL peak related to 2DEG can be observed at the temperature as high as 80K. The PL intensity was enhanced by the existence of the thin layer of $Al_xGa_{1-x}N$ (where x in the samples varied from 10 to 17 percent) grown onto the GaN layer, thus suppressing the diffusion of photo-excited holes. A total of five samples was measured.

2. Experiment

The characterized GaN wafers were prepared by CREE Research, Durham, NC, and were delivered to the U.S. Army Research Laboratory (ARL) as residuals in accordance with an ARL small business initiative research (SBIR) contract. AlGaN/GaN epilayers were grown on SI 4H-SiC wafers by metal organic chemical vapor deposition (MOCVD) with an insulating Aluminum nitride (AlN) buffer layer to achieve high quality GaN. The general epilayer structure for the subsequent device process is comprised of a thin AlN nucleation layer, 2 μm of undoped GaN and 12 nm of $Al_xGa_{1-x}N$ with Al mole fraction in the range of 10 to 12 percent and 15 to17 percent. As shown in Figure 1, the AlGaN cap is nominally grown with a 5-nm undoped spacer layer, a 12-nm Si-doped donor layer ($\sim$2-5e18/cm^3), and a 10-nm undoped barrier layer. Subsequent device processes included device isolation achieved with etching using reactive ion etching (RIE). Ohmic contact was then obtained with liftoff of Ti/Si/Ni annealed at 900C. Standard T-gate of different gate lengths and 2-μm thick gold overlayer metal was employed.

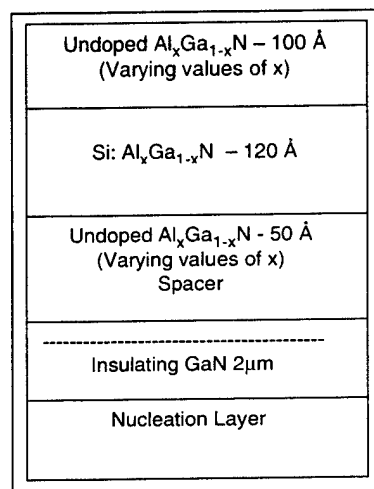| |
|---|
| Undoped $Al_xGa_{1-x}N$ – 100 Å (Varying values of x) |
| Si: $Al_xGa_{1-x}N$ – 120 Å |
| Undoped $Al_xGa_{1-x}N$ - 50 Å (Varying values of x) Spacer |
| Insulating GaN 2μm |
| Nucleation Layer |

Figure 1. $Al_xGa_{1-x}N/GaN$ heterostructures with an n-type donor layer having various donor concentrations of 2×10^{18} to 5×10^8 cm^{-3}.

The five samples tested have the dimensional parameters for the material structures as given in Table 1. Percentages of Al mole fraction and corresponding doping levels are also indicated. These samples were subjected to PL measurements at different temperatures between 10 and 100 K. The 325-nm line of a continuous wave helium-cadmium (CW He-Cd) laser operating at 50 mW was employed as the source. A variable intensity filter was used to change the laser intensity. The PL measurements were performed with a 0.85-m double-path spectrometer (Spex model 1404) with the detector being a Hammamatsu water-cooled GaAs photon multiplier tube. A Janis cryogenic cooler was used to cool the sample.

Table 1. Sample Structure Parameters

Sample No.	Spacer layer		Doped layer		Undoped layer		
	Thickness	Al %	Thickness	Al %	Doping level, $\times 1018$ cm^{-3}	Thickness	Al %
F - 06	50 Å	13	120 Å	13	5	100 Å	13
F - 09	50 Å	15-17	120 Å	15-17	2	100 Å	15-17
F - 10	50 Å	13	120 Å	13	2	100 Å	13
F - 11	50 Å	10-12	120 Å	10-12	2	100 Å	10-12
Q - 17	50 Å	15-17	120 Å	15-17	2	100 Å	15-17

3. Results and Discussion

Figure 2 shows the PL spectrum of one of the samples (F-09) of modulation-doped $Al_{0.15}Ga_{0.85}N$/GaN heterostructure measured at 10K. The photon counts per second is plotted against wavelength. The peaks at 360.04 (3.444 eV) and 367.40 nm correlate the recombination of the FEs consistent with phonon replica. An additional peak as indicated by an arrow in Figure 2, at 357.95 nm, corresponding to higher energy of 3.464 eV was also observed. This peak, even though it is broad and weak, cannot be accounted for in bulk GaN. It is about 20 meV higher than the peak of the FE emission. The doping of the $Al_{0.15}Ga_{0.85}N$ is necessary for the observation of this peak.

Figure 3 shows the PL spectra of the same sample (F-09) measured at different temperatures between 10 and 70 K. The intensity of the additional peak (observed previously) at 357.95 nm (3.46 eV), as indicated by an arrow decreases as the temperature increases. This behavior is consistent with PL peak shifts to lower energy with increasing temperature dependence related to existence of 2DEG, and the energy distance between the photo-excited holes.

Another PL measurement experiment was performed on another sample (F-11) with varying excitation intensities at fixed temperature,10 K. The intensity of the laser beam was changed by varying neutral density filters. The measured PL spectra are shown in Figure 4. Even at the low intensity of 5 mW, the additional peak, is still visible and it is not as broad as in the previous sample. As the intensity increases, the photon count peaks increase and the corresponding

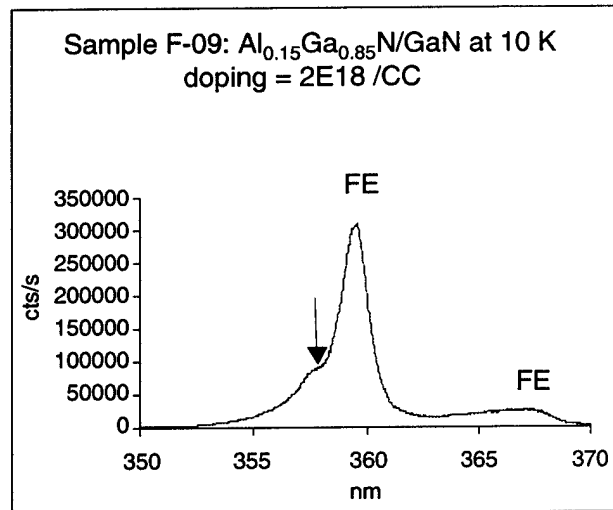spectra broaden. The peaks also shift to the higher energy along with the FE peak as shown in Figure 4.

Figure 2. Photoluminescence spectrum of a modulation-doped $Al_{0.15}Ga_{0.85}N/GaN$ heterostructure at 10 K. (An additional peak at 357.95 nm (3.46 eV) is indicated by an arrow.)

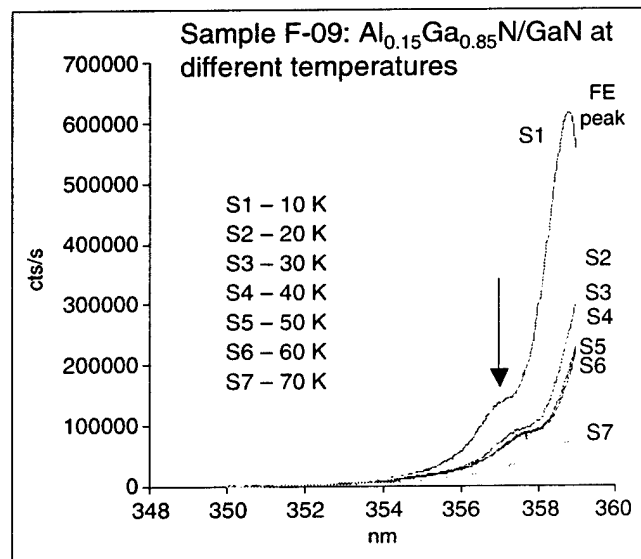Figure 3. PL spectra of modulation-doped $Al_{0.15}Ga_{0.85}N/GaN$ heterostructures at different temperatures. (The additional peak, indicated by an arrow, shifts to lower energy with increasing temperature.)
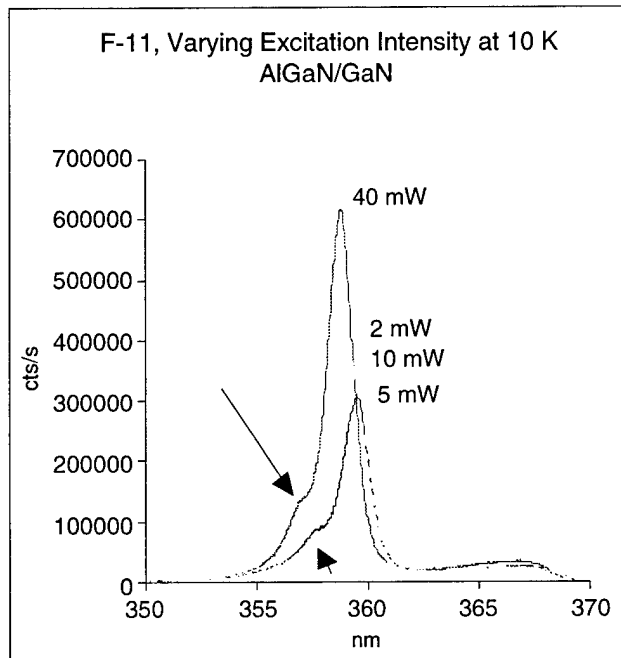
4

F-11, Varying Excitation Intensity at 10 K
AlGaN/GaN

700000
600000
500000
400000
300000
200000
100000
0

cts/s

40 mW
2 mW
10 mW
5 mW

350   355   360   365   370
nm

Figure 4. PL spectra of modulation-doped $Al_{0.15}Ga_{0.85}N/GaN$ heterostructures at different intensities. (The peaks attributable to the possible 2DEG are indicated by the arrows.)

The other three samples that were also measured showed similar behavior but with weaker peaks; these results suggest that the 357.9-nm feature can be attributed to the recombination of the 2DEG with photo-excited holes at the AlGaN/GaN interface. These material structures were used to fabricate high electron mobility transistors (HEMT) devices by CREE Research. Optimum microwave performance has been found in devices fabricated on material structure similar to the sample F-09. Power performance has yielded a device power density of 6.8 W/mm and power added efficiency of 52 percent at 10 GHz [11]. In our experiment, the same sample also indicated the best additional PL peak at 357.95 nm (3.46 eV), leading to the possibility of the observed peak attributable to 2DEG effect.

4. Conclusion

A number of samples of $Al_xGa_{1-x}N/GaN$ (where x varies from 10 to17 percent) were used in PL measurements at various temperatures and laser intensities. In all samples, the PL peaks related to the possible recombination between 2DEG and photo-excited holes of a modulation-doped $Al_xGa_{1-x}N/GaN$ heterostructure at 10 K were observed. In one sample with 15 percent Al mole fraction structure, $Al_{0.15}Ga_{0.85}N/GaN$, a broad PL peak of 3.46 eV at 357.95 nm, was observed. This peak value is about 20 meV higher than the peak of the FE emission. The peak can be observed at temperatures as high as 140 K. However, this peak cannot be seen in bulk GaN.

Therefore, in this particular structure, one explanation for the enhanced PL intensity is the result of incorporating a thin layer of $Al_{0.15}Ga_{0.85}N$ into the GaN to confine the photo-excited holes inside the hetero-interface region. When the temperature was increased, the energy difference between the PL peak related to the likely 2DEG and the FE emission decreased and the PL peak shifted to lower energy with increasing temperature. In another experiment, the observation was made that at high excitation intensity, PL spectra related to the possible recombination between 2DEG and photo-excited holes of a modulation-doped heterostructure shifted to higher energy side. At lower excitation intensities, PL spectra shifted to lower energy side. The peak intensity increased approximately linearly with excitation intensity in all cases. The sample with the most prominent non-FE peak has similar material structures upon which HEMT devices with excellent power density and efficiency performance at microwave frequency have been reported. Finally, additional experiments to confirm the observed PL because of the 2DEG can be implemented by removing the AlGaN layer with RIE and repeating the PL experiments from the structures without the 2DEG at the interface.

Acknowledgment

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